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Study of briquetted biomass co-firing mode in power plants

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HIGHLIGHTS

- The biomass co-firing mode is suitable for biomass dispersedly distributed areas.
- High economy and efficiency of biomass pretreatment can be realized.
- The biomass can be used through existing equipments efficiently and cleanly.
- Economic analysis shows that this mode is of good economic sustainability.

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ABSTRACT

A briquetted biomass co-firing mode that is feasible in China and other areas with dispersedly distributed biomass resources was proposed, and the details and characteristics of this mode are discussed. Raw biomass from sources such as corn stalks, twigs, and straws was crushed in farmlands and then transported to briquetting stations. The crushed biomass was dried and compressed into briquettes until the moisture content was less than 25%. Finally, the biomass briquettes was stored and delivered to plants like coals for combustion. One of the six layers of the pulverizing system in a 300 MW power plant could be used, and 100% biomass briquettes could be ground by an existing MPS medium speed pulverizer. The biomass briquettes could then be delivered directly into the furnace by primary air. No additional equipment investments were needed for the plant because almost all equipments were already available. Advantages such as cost-effective on biomass collection and transportation, high efficiency and low cost on biomass preprocessing, biomass briquette economic grinding and feeding, and efficient and clean combustion could be realized by this method. The economic sustainability of this mode was also analyzed.

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1. Introduction

Coal-fired power plants account for more than 70% of the total power generation capacity in China. This large-scale coal consumption results in severe CO_2 emissions. China has been ranked No. 1 in CO_2 emissions since 2009. Thus, plans have been made to reduce CO_2 emission by 55%–60% by 2020 under different macro-control measures of the state. Renewable energy is important to achieve energy savings and reduce CO_2 emissions.

Biomass is considered a CO_2-neutral fuel because biomass consumes the same amount of CO_2 from the atmosphere during growth and combustion. It yield in China is approximately 1.17 billion tce/a, 48% of which can be used for power generation [1,2], compared with the total potential bio-energy in the whole world (i.e.,3.42 tce/a to4.95 tce/a (2050)) [3].

Biomass power generation will reach 13,000 MW by 2015 with an estimated electricity price of 0.122 USD/kWh, which is higher than the electricity from a coal-fired power plant (0.054 RMB/kWh) [4], according to the documents released by the National Energy Administration of China. However, subsidy is only provided for dedicated biomass firing power plants and does not cover coal/biomass co-firing plants, which have unmanageable co-firing ratios and quantities.

Dedicated biomass firing plants have rapidly developed in recent years under the support of government policy. Over 100 dedicated biomass firing plants are distributed in China [5]. However, in biomass direct-firing power generation, the alkali metal and particularly high content of potassium and chlorine in biomass lead to severe slagging and corrosion [6–11]. The thickness of the slagging on superheaters can reach 900 mm after operating for only a month in some boilers [6,7]. Nevertheless, biomass co-firing in large-scale thermal power plants can significantly ease slagging

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and corrosion problems [12–16]. The thermal parameter of dedicated biomass firing power plants is lower than the thermal parameter of large-scale pulverized coal (PC) boilers. The combustion and overall power generation efficiencies are lower than 85% and 25% for dedicated biomass firing boilers, respectively. For large-scale co-firing PC boilers, the power generation efficiency can be higher than 40% [17,18]. Furthermore, the sensitivity of co-firing plants to biomass supply price is lower than the sensitivity of biomass direct-firing plants. Co-firing plants can adjust their co-firing ratios according to the price and supply of biomass. Previous studies have shown that biomass co-firing can reduce $CO_2/SO_2/NO_x$ emissions without affecting the operation of the units if the biomass co-fired quantity is controlled at a reasonable level [12–15,19]. Most coal power plants in England are subject to the requirement of at least 5 cal% co-firing capability. However, such biomass co-firing power plants are few in China.

The first demonstrated PC/straw co-firing power plant in China began operations in Shandong Province in 2005 [20]. The technology from Burmeister&Wain Energy A/S, Denmark, is introduced in this paper. A new set of straw transport and mill equipment are installed, and two straw burners with 30 MW input ability are equipped in the middle of the original two-layer PC burners. Air supply systems and associated control systems are also improved. However, the adaptability of the straw pretreatment equipment is weak, and only wheat straw can be processed. The excessive dependence on a single type of biomass has led to the sharp increase of biomass price from 30 USD/t to nearly 80 USD/t. Nevertheless, the plant can obtain small profits by obtaining a subsidy of 0.0127 USD/kWh from the local government. The family pattern agricultural production structure in China differs from ranches in Western countries. Such a small scale farming structure scatters straw resources and increases the difficulty of straw collection and transportation. The biomass used in plants is simply packed with low bulk density. This biomass co-firing mode has not been extended to other parts of China because of these afore mentioned reasons.

A new biomass co-firing mode, which has been applied in a 300 MW unit in Baoji, Shaanxi Province, is proposed in this study to explore a suitable biomass co-firing mode for China or other areas with distributed biomass resources. This mode has been implemented for two years. The details and characteristics of this mode are discussed in this paper.

2. Mold biomass co-firing mode

2.1. Background of the mode

This biomass co-firing mode has been applied in a coal-fired power plant in Baoji, where is the major-grain producing area in Shaanxi Province and is also one of the major wheat and cotton-producing areas in China. Crop straw output in Baoji is approximately 2.7779 million t in 2008, accounting for 12.17% of the total output in Shaanxi Province, among which 49.2% of the total straw is used for daily cooking or warming [21]. Furthermore, about 24 million t of straw are discarded or burnt in fields, causing energy waste and serious atmospheric pollution [21]. To make full use of this straw resource, USD 5.55 million has been invested by the Shaanxi government and China Guodian Group to promote mold biomass co-firing in large-scale coal-fired power plants.

2.2. Details of the co-firing mode

A mold biomass co-firing mode in 2 × 300 MW PC power plant is proposed. This co-firing mode would be described detailedly in three major areas: fuel characteristics, biomass pretreatment, feed system and combustion organization.

2.2.1. Fuel characteristics

The plant in this case commonly uses Huating bituminous coals, and the co-fired biomass briquettes are made from straws, corn stovers, tobacco poles, branches, and other agriculture wastes. The proximate and elemental analyses of the bituminous coal and co-fired biomass are listed in Table 1. Biomass briquettes are highly volatile and contain lower carbon, sulfur, and calorific values than Huating coal. The density of biomass briquettes is 780 kg/m^3 to 1180 kg/m^3, which is significantly higher than that of raw biomass (50 kg/m^3 to 120 kg/m^3 for wheat straw and other soft straws; 200 kg/m^3 to 350 kg/m^3 for corn stalks and other hard straws; 125 kg/m^3 for rice husk). The briquettes have cylindrical shapes, 34 mm diameters, less than 65 mm lengths.

2.2.2. Supply, pretreatment, and storage of biomass fuel

The supply chain of biomass is designed in accordance with the family patterns of farming in China as follows: farmers → straw brokers (briquetting station) → power plant. The power plant contacts and develops a group of straw brokers and assists them in establishing biomass briquetting stations. The straw brokers then purchase raw biomass from dispersed farmers within about 50 km around the briquetting station. Raw biomass is crushed once collected in fields to reduce its volume. Then the crushed biomass is dried in air until the moisture content is less than 25% and then compressed into briquettes at the briquetting station. The process capacity of each set of briquetting equipment is 0.8–1.0 t/h. Then the processed briquettes are sent to the power plant for co-combustion with coal. The local government donates one set of briquetting equipment to biomass brokers per equipment purchased to encourage biomass brokers to establish straw briquetting stations. A total of 19 straw briquetting stations currently exist within 100 km around the plant and are equipped with 50 sets of briquetting equipment. The number of briquetting stations is still increasing.

2.2.3. Feed system and combustion organization

The boiler used in the presented case (DG1025/18.3) is designed and manufactured by Dongfang Boiler Work (China), with a capacity of 300 MW and an evaporation time of 1025 t/h, which is equipped with a four-corner fired combustion system. The layout of combustors is shown in Fig. 1. Six layers (A–F from bottom to top) of combustors comprise the combustion system, and each layer is equipped with an individual mill system and primary air injectors. The five layers (A–E) are used to maintain maximum continuous rating operating conditions. A group of MPS medium speed pulverizer and direct-blowing pulverizing system exists in each layer. The remaining layer (F) is used to grind and burn biomass briquettes.

The design of a biomass feeding system is one of the key issues [13] in biomass co-firing power generation. Two major types of biomass feeding systems exist for a biomass co-firing plant: (1) biomass feeding system that mixes biomass directly with coal at

Table 1
Proximate and ultimate analyses of tested fuels.

Fuel	$Q_{net,ar}$/ $MJ\ kg^{-1}$	Proximate analysis			Ultimate analysis				
		M_{ar}	V_{daf}	A_{ar}	C_{ar}	H_{ar}	O_{ar}	N_{ar}	S_{ar}
Coal	18.7	18.5	35.5	17.6	52.5	3.03	9.96	0.51	0.64
Biomass briquette	12.2	10.1	79.3	6.5	44.7	3.43	44.2	0.81	0.30

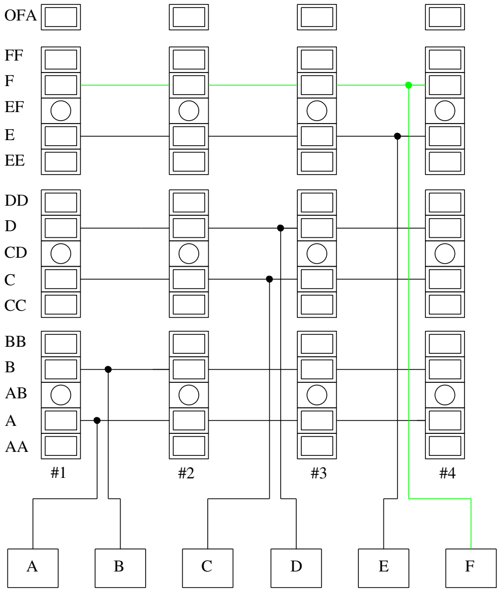

Fig. 1. Schematic of feed system and layout of combustors.

the upstream and then delivers the coal into the boiler by the coal feeding system; (2) a dedicated biomass fuel feeding system that is parallel to the PC pipeline is used to deliver fuel into the boiler separately.

The feeding system used in this mode differs from the above mentioned two systems. The detailed process is shown in Fig. 2. The biomass briquettes purchased from straw brokers are delivered to the coal bunker of layer F by conveyor belt. The biomass briquettes are then ground in an MPS medium speed pulverizer and directly delivered into the furnace by the primary air from layer F for combustion. Additional equipment investments are not needed because almost all types of equipment needed for biomass briquette grinding and feeding are already available in the power plant.

For the combustion organization, the volumetric flow rate of the primary air in combustor F and the ratio of OFA are maintained unchanged basically at different biomass blend ratio. Then the primary air temperature of combustor F is reduced to 80 °C (about 229 °C for coal) to avoid the biomass self-ignition. Furthermore, the oxygen concentration at the furnace outlet is kept at about 1.19 through adjusting the primary air from burners A–E.

2.3. *Characteristics of the biomass co-firing mode*

2.3.1. *High economic performance on collection and transportation*

The scattered distribution of biomass resources in China significantly restricts the large-scale use of biomass because of the high costs incurred on biomass collection and transportation in addition to biomass disadvantages of low bulk density, high moisture content, and unspecified form and size. A plant can directly purchase processed briquettes from briquetting stations established according to local biomass distribution condition for the co-firing mode proposed in this study.

Table 2
Comparison of pellets, TOPs and briquettes.

Name	Simple pellets	TOP pellets	Briquettes
Moisture content (%)	7–10	1–3	12–25
Calorific value (MJ/kg)	15–16	20–24	11–12
Bulk density (kg/m^3)	550–750	750–850	500–750

Raw biomass is directly crushed in the field by using a diesel crusher installed on a hand tractor during collection to reduce biomass volume. The volume of crushed biomass is lower by approximately 70% than raw biomass and biomass parcels. Only one operator is needed for the straw crusher, and the purchasing price and maintenance cost are low because of the easy operability and low price of hand tractors and diesel crushers. The significant decrease in collection and transportation costs also increases the economic collection radius of biomass. The optimal collection radius of biomass power plants is approximately 50 km [22]; however, the purchasing scope covers the whole region of Baoji. A briquetting station will also be established in Hanzhong, which is 100 km away from Baoji, if the co-firing mode is adopted. A large collected radius ensures the reliability of biomass fuel supply for the plant.

2.3.2. *High efficiency and low-cost biomass preprocessing*

Biomass must be dried before briquetting to meet the requirement of biomass briquetting machines because of the high moisture content (40%–50%) of crushed biomass. Investigations have shown that the optimal moisture content of feedstock should be 12% or less if the moisture content of the final pellets is controlled at 6%–8% during biomass processing into pellets. This process is commonly used in European nations. Investigations have also shown that the moisture content will be less than 3% if biomass is torrefied. Biomass torrefaction enables the efficient manufacturing of biomass. However, torrefaction technology is still immature.

Flue gas dryers and superheated steam dryers are commonly used dryers. However, scattered biomass resources in China cannot be subjected to flue gas or superheat steam, which requires a large amount of energy. Briquetting aims to improve the density and grindability of biomass in this co-firing mode. Biomass briquettes will then be ground in a coal mill. Self-designed biomass briquetting machines are adopted, and biomass is processed into briquettes with equivalent moisture contents and lower bulk densities than pellets and torrefied pellets (TOPs).

Crushed biomass should be dried at a straw briquetting station before briquetting. The moisture content of sun-cured biomass may decrease to 12%–25%, which meets the operation requirements of briquette machines. Sun curing and drying is adopted to reduce

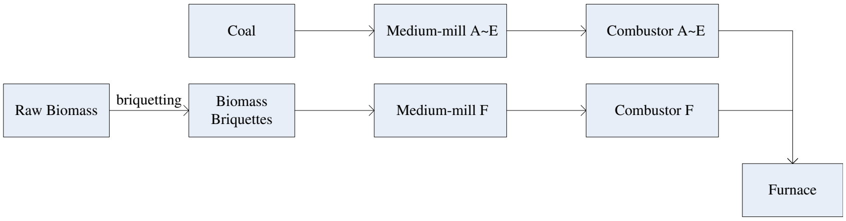

Fig. 2. Biomass briquettes feeding.

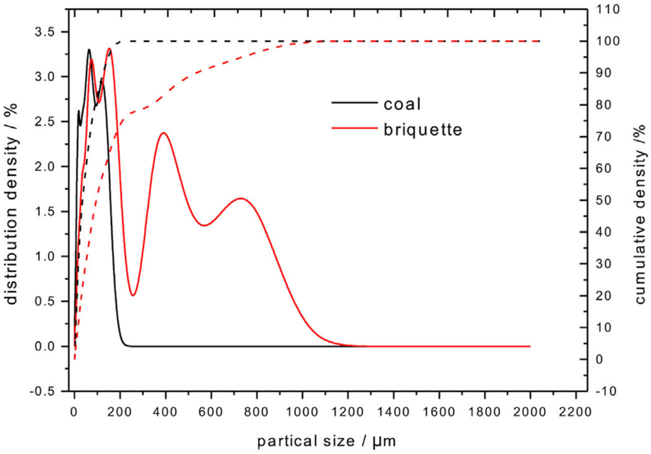

Fig. 3. Size distribution of ground biomass briquettes.

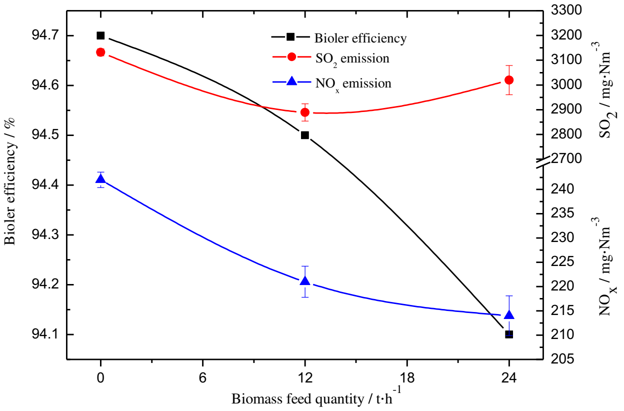

Fig. 4. Effects of biomass feed quantity on boiler efficiency, SO_2 emission and NO_x emission.

energy consumption significantly compared with the above mentioned dryers. The drying field in the rural area is abundant and the field cost is lower. All these factors make briquettes suitable for the co-firing mode proposed in this paper.

A comparison among the properties of simple pellets, TOPs, and briquettes is presented in Table 2. The bulk density and power consumption of briquettes is lower than the bulk density and power consumption of simple pellets and TOPs. Briquetting machines also have higher adaptability to the moisture content of biomass than the other two preprocessing methods. Therefore, this biomass preprocessing method is efficient and economically feasible in Western China and other underdeveloped areas.

2.3.3. *Economic grinding and feeding of mold biomass*

Grinding costs and technology to prevent biomass self-ignition during pulverization must be considered for co-fire biomass in existing large-scale PC furnaces. Excessive biomass feed quantity will increase the electric current of the mill beyond the safety limits when biomass crushes are ground in existing coal mill systems, thus resulting in the blockage of primary air pipes and reducing the safety of the mill system.

Biomass briquettes are harder and have better grindability than biomass crushes. In this utilization mode, biomass briquettes are ground by an MPS medium speed pulverizer and then blown into the furnace via the burners at layer F. Fig. 3 shows the particle size distribution of ground biomass. The particle size of coal is smaller than the particle size of biomass. Most coal particles are smaller than 160 μm, whereas the biomass briquettes are smaller than 800 μm. Biomass particle sizes smaller than 200 and 850 μm accounts for 75% and 97%, respectively, which meet the demand of combustion. Therefore, additional grinding and feeding equipment are not needed in this mode.

2.3.4. *Efficient and clean combustion*

Fig. 4 shows the effects of biomass feed quantity on boiler efficiency, NO_x emission, and SO_2 emission. The boiler efficiency decreases slightly at high biomass feed quantities. The boiler efficiency only decreases slightly to 94.1% from 94.7% when the co-fired biomass quantity reaches 24 t/h (17.4 wt% and 12.3 cal%). The combustion efficiency of biomass in large-scale units is significantly higher than in biomass direct-firing boilers with low thermal parameters. However, boiler efficiency decreases with the increasing biomass feed quantity.

Fig. 4 indicates that NO_x emission is reduced by approximately 10% with a 24 t/h biomass feed quantity, even if the nitrogen content of biomass briquettes is slightly higher than that of coal. During the co-firing process, the ratio of OFA and the volumetric flow rate of the primary air in top combustor F are maintained largely unchanged and the oxygen concentration at furnace outlet is kept at about 1.19. The lower temperature of the primary air at combustor F makes its mass flow rate much higher than that at lower combustors. Then the increased air from the top combustor F leads to the decrease of fraction of air from the rest of the burners. The calculation shows that the overall equivalence ratio of the furnace is always in rich-oxygen conditions and the overall equivalence ratio before the top burner reduced to 0.96 (24 t/h biomass input), and this contributes to the reduction of NO_x.

SO_2 emission decreases slightly for biomass co-firing, and the maximum decrease is only 140 mg/Nm^3. The sulfur content of biomass is approximately half of the sulfur content of coal according to the ultimate analysis, and the biomass used here is not low-sulfur fuel at all. The feed quantity of biomass is twice as that of coal for the same heat input. Therefore, with larger biomass blend ratio, the total sulfur input into furnace will not decrease obviously. Otherwise, error analysis of SO_2 emission in Fig. 4 indicates that the higher biomass blend ratio is, the larger the fluctuation of

Table 3
Test results for the major parameters of mortars with fly ash [17].

Mortar type	Standard mortar	Testing mortar with fly ash		
		With no biomass co-firing	Biomass feed quantity 12 t/h	Biomass feed quantity 24 t/h
Water demand ratio (%)	100	91.15	88.50	88.50
Expansion (mm)	0.50	1.25	1.75	1.75
Flexural strength (7 days) (MPa)	6.40	4.90	4.95	5.05
Tensile strength (7 days) (MPa)	36.70	25.30	23.55	22.30
Flexural strength (28 days) (MPa)	8.70	8.95	8.95	8.60
Tensile strength (28 days) (MPa)	49.6	39.95	37.95	37.45
Activity index	100	80.55	76.50	75.50

combustion in furnace presents. These two reasons cause the slightly increase of SO_2 at 24 t/h. Generally speaking, SO_2 emission at co-firing condition is slightly lower than that at coal condition.

Other experiments conducted in pulverized coal furnace, bubbling fluidized bed boiler and some circulating fluidized bed boiler also indicated that the NO_x concentration in flue gas would decrease at biomass/coal co-firing condition [13,23,24], while there are also some investigations show the contradictory result because of the different feedstock port locations in the CFB boiler and the higher nitrogen content in biomass [25]. Furthermore, some other researches also indicated biomass/coal co-firing can reduce the SO_2 emissions, and even cause more significant reductions than our case [14,23,26]. For furnace efficiency, researches had been done to indicate that the biomass co-firing can decrease the furnace efficiency by 1–2% relating to different quality of fuel, furnace construction, operation of mill system and the whole combustion [14,27].

The feasibility of using fly ash produced by biomass co-firing in cement is studied according to Chinese Standard GB/T1596-2005. Testing mortars are made by blending the fly ash with standard contrast samples. Key parameters such as water demand ratio, expansion, flexural strength and tensile strength at 7 d and 28 d, and activity index are tested. The main test parameters mentioned above are listed in Table 3. The result indicates that the fly ash produced in the presented biomass co-firing trial can be used in cement and concrete industries even though the activity index slightly decreases.

Slagging is commonly obvious in biomass direct-firing power plants, near the combustors, or on the surface of heat exchangers. However, no problem of slagging occurs according to the two-year operation of this co-firing mode. The reasons can explained as some additives like local soil were added into the briquettes during the briquetting process. And this is also the reason for the high ash content in biomass briquettes. Higher ash content and relatively low blend ratio cause the unobvious slag in furnace.

3. Sustainability of co-firing mode

Fuel cost accounts for more than 70% of the total operation cost of biomass energy power generation; thus, fuel cost determines the sustainability of power generation. Biomass power plants have few incentives to determine the biomass price because the biomass market in China is a seller's market. Therefore, power plants can rarely gain any profits from the upstream of the biomass supply chain. Flexibility in the co-firing ratio can reduce the dependence of plants on biomass supply and provide plants with more choices during fluctuations in biomass prices. The additional cost of biomass co-firing mainly includes raw biomass purchasing, biomass pretreatment, biomass transportation, and initial equipment investment. The economical sustainability of this co-firing mode is discussed in this section.

3.1. Purchase costs of biomass briquettes

The plant has higher adaptability on biomass species in the proposed biomass co-firing mode. Straws, tobacco rods, branches, and other hard types of biomass can be pretreated and utilized; thus, the plant can choose different types of biomass according to market conditions. The current purchasing price of local raw biomass from farmers is between 24.5 and 40.8 USD/t according to our investigation.

Table 4 shows the power and processing capacity of briquetting machines. The power consumption for briquetting is approximately 34.7 kWh/t. Given the electricity price of 0.16 USD/kWh, the cost on electricity for pretreatment is approximately 5.66 USD/t. Eight workers are needed, and the salary for one worker is approximately 16.31 USD/d, which is equivalent to 6.52 USD/t in a briquetting station with a production capacity of 20 t/d. About 1.14 USD/t are needed for machine maintenance and management. Thus, the total biomass pretreatment cost is approximately 13.32 USD/t.

Table 4
Power and processing capacities of biomass pretreatment machines.

Pretreatment machine	Power kW	Processing capacity t h^{-1}	Power kWh t^{-1}	Price US $
Conveyor	6	3	2.0	3910
Crusher	20	5	4.0	2450
Rubbing machine	20	3	6.7	2450
Briquetting machine	22	1	22	14,680

Biomass is commonly transported by vehicles with a load capacity of 10 t. The average transportation cost for each vehicle from a briquetting station to a plant is approximately 81.55 USD, i.e., the transportation cost of biomass briquettes is 8.15 USD/t.

The total cost of briquettes is the sum of raw biomass purchase, pretreatment, and transportation costs. When the raw biomass collection price is 32.62 USD/t, the purchasing price of biomass briquettes for a power plant is approximately 69.63 USD/t plus 17% taxes and10%profits.

Fig. 5 shows the relationship between the standard coal price and raw biomass purchasing price with different calorific values. The curves are boundaries to evaluate whether the biomass/coal co-firing mode are economic feasible. Actually, each curve represents the coal and biomass can realize same economy performance. At the top regions of the curves (region A), the biomass price is lower and the coal price is higher, so the biomass blend ratio should be increased on the condition of technical feasibility. On the contrary, at the bottom regions of the curves (region B), the biomass price is higher and the coal price is lower, so the biomass blend ratio should be decreased. The plant mentioned above is adopted as an example. If the standard coal price is lower than 142 USD/t, the co-firing mode can operate sustainably when the raw biomass purchasing price is 24.5 USD/t and the biomass briquette calorific value is 12.2 MJ/kg. The price of steam coal (5500 kcal) at Xi'an is 94.6 USD/t to 127.2 USD/t, which is equivalent to 120.4 USD/t to 162.0 USD/t of standard coal. Subsidies are offered by the local government to promote biomass utilization. Therefore, the co-firing mode can be continuously implemented in a wide price range with small subsidies by appropriately adjusting the blending quantity of biomass.

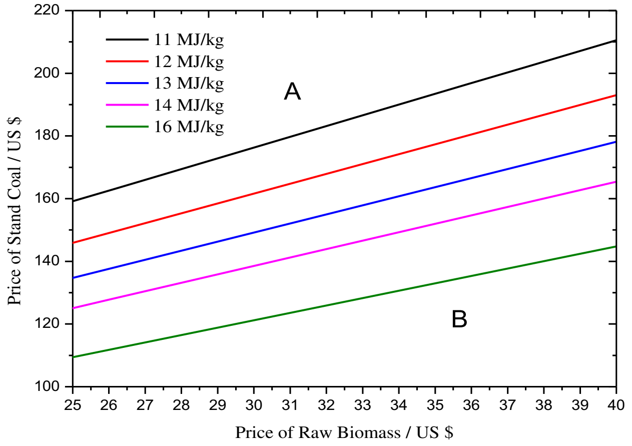

Fig. 5. Sustainability of the proposed co-firing mode.

3.2. Initial investment on equipment

No additional equipment is needed in the power plant if the proposed co-firing mode is adopted. The investment for this mode almost only includes biomass pretreatment machines that are used in briquetting stations. The average equipments in a briquetting station are a conveyor, a crusher, a rubbing machine and three briquetting machines. Table 4 indicates that about 52,850 USD are needed for a briquetting station. To date, 19 briquetting stations have been established with 57 sets of briquetting equipment, which has a total initial investment on equipment of about 1,004,150 USD. For comparison crushing and feeding equipment, as well as biomass burners, are required in addition to biomass preprocessing equipment for the co-firing plant in Shandong Province mentioned in the Introduction, wherein the burners alone cost about 13,048,000 USD.

4. Conclusions

A new biomass co-firing mode, which is applicable in China and other areas with distributed biomass resources, is proposed in this paper. The characteristics of the proposed co-firing mode are as follows:

a. Biomass is pretreated into briquettes, which has stronger flexibility on biomass species and moisture content, and the cost on preprocessing is lower than that of simple or TOPs.
b. The original MPS once through pulverizing system on the boiler can be directly used in this mode, with desirable grinding and burning effects.
c. Efficient and clean combustion can be realized in this mode, i.e., boiler efficiency may decrease by 0.6%, NO_x emission may decrease by 10%, SO_2 emission may decrease by 100 mg/Nm^3 to 200 mg/Nm^3, and ash utilization in cement is unaffected.
d. The biomass blend ratio can be adjusted according to market conditions. The proposed mode is more sustainable for biomass dispersedly distributed areas than other existing modes.

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